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DETERMINATION OF SEISMIC SOURCE DEPTHS FROM
DIFFERENTIAL TRAVEL TIMES

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ENSCO, Incorporated

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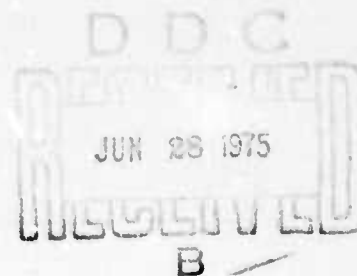
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FROM DIFFERENTIAL TRAVEL TIMES

QUARTERLY REPORT

May 1975



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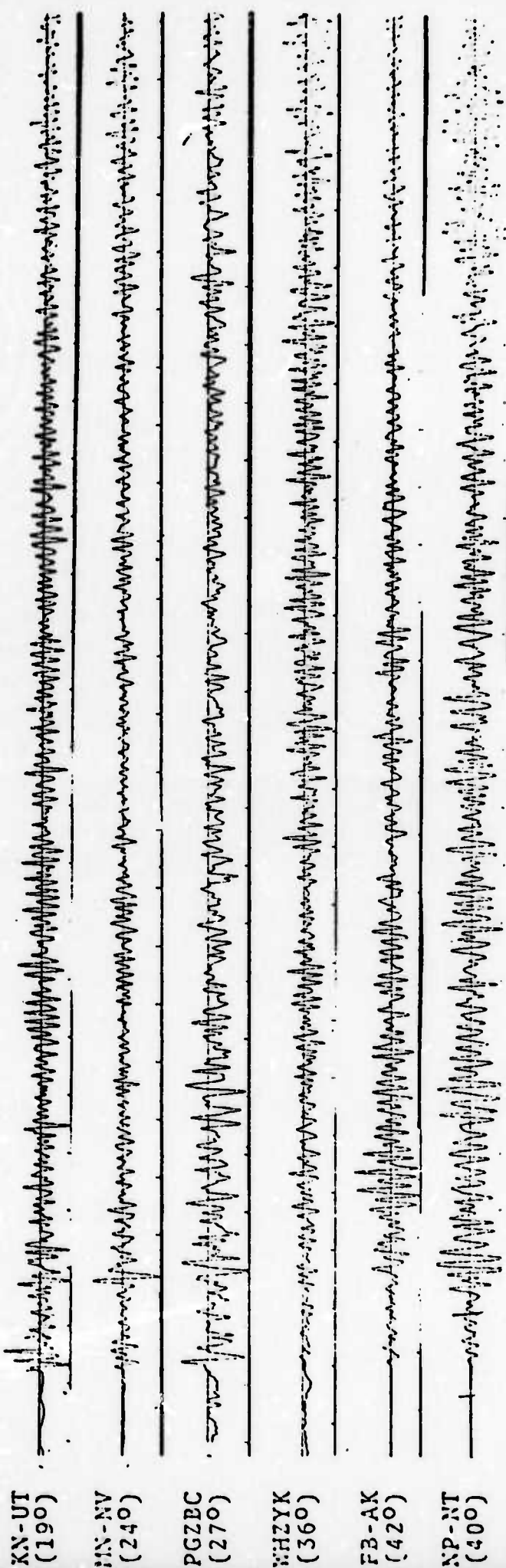
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Introduction and Summary

The objective of the current project is to improve seismic depth phase detection by exploiting information contained in the seismic coda. During the first quarter of this project we have analyzed a well-understood event and clearly demonstrated that depth phase detection can be enhanced through proper analysis of the seismic coda. During this quarter we also indicated how a cepstrum matched filter technique can automate the interpretation of the computed cepstrum and extract depth phase estimates.

Major Accomplishments

The Illinois Event of September 11, 1968, was analyzed using data recorded at six LRSM stations. The pP phase can be visually identified for the event from the first arrival portion of the seismogram (see Figure 1), and are observed to have an ~7.0-second delay. From the travel time charts one can find that the sP phase is expected at ~10-second delay. Analysis of a cepstrum computed by averaging 6 cepstrums computed using 12.8-second samples (first arrival portion) from each of the six stations, gave a clear detection of the pP phase as is shown in Figure 2a. The cepstra were weighted before averaging such that their mean amplitudes were equal. However, by averaging 30 cepstra computed from five consecutive 12.8-second samples of data from each of the six stations, both pP and sP delay times are clearly detected as is shown in Figures 2b and 2c. Note that these cepstrums are in agreement with the cepstrum computed



ILLINOIS EVENT (9/11/68)

(5 sec tic mark)

Figure 1

Figure 2a

CEPSTRUM STACK;
(1st - 12.8 SECOND SAMPLE
FROM EACH STATION)

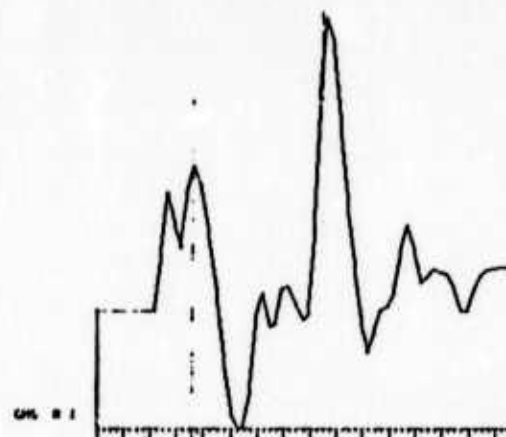


Figure 2b

CEPSTRUM STACK
(5 - 12.8 SECOND SAMPLES
FROM EACH STATION)

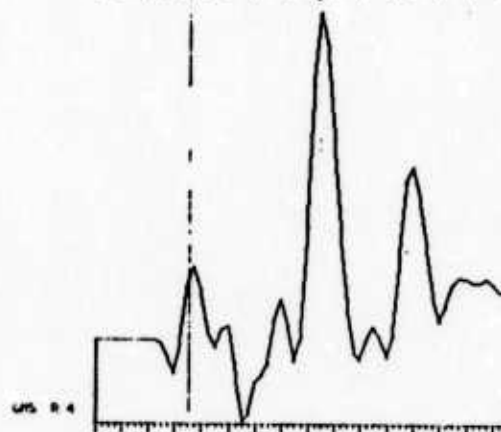


Figure 2c

CEPSTRUM PHASOR STACK
(5 - 12.8 SECOND SAMPLES
FROM EACH STATION)

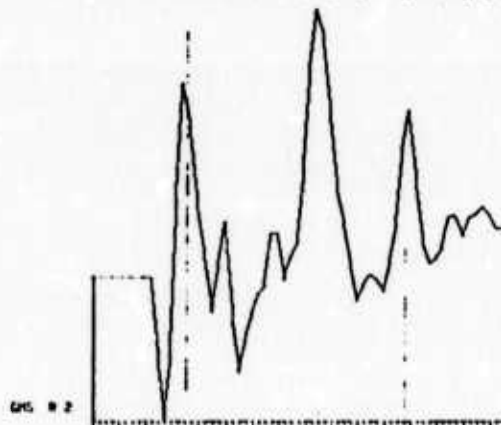
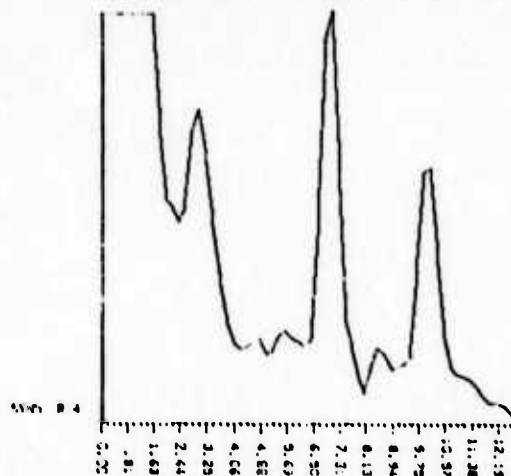


Figure 2d

SYNTHETIC CEPSTRUM STACK
($T_1 = 7.0$; $T_2 = 10.0$)



from synthetic data for 7 and 10-second delay times. (The results shown were computed using consecutive data samples from each seismogram. Very similar results were obtained when the data samples were consecutively overlapped both 50% and 75%.)

To further illustrate that useful depth phase information is contained in the coda, we omitted the first 12.8-second portion (that portion used for visual identification) of the seismogram from the analysis and analyzed the next five consecutive 12.8-second samples. As can be seen from Figure 3a, clear identification of the pP and sP depth phase is still achieved demonstrating that the additional depth phase information contained in the seismic coda can enhance depth phase detection when properly incorporated in the analysis. (Results of the analysis at the individual stations are shown in Figure 4.)

Care must be taken in utilizing the seismic coda since delay times between later seismic arrivals and their associated surface reflected phases, generally differ from those of the pP and sP delay times. Thus, by averaging cepstrums computed from different portions of the coda, one may lose detection of those cepstrum peaks which correspond to the pP and sP phases. If these delay time variations are not too large, depending on the distances, depths, and phases involved, this problem can be adequately accounted for using the stochastic stacking technique. If these variations are too large for this procedure then the delay time as a function of the position of the sample along the coda can be approximately accounted for through travel time tables for the later surface reflected phases

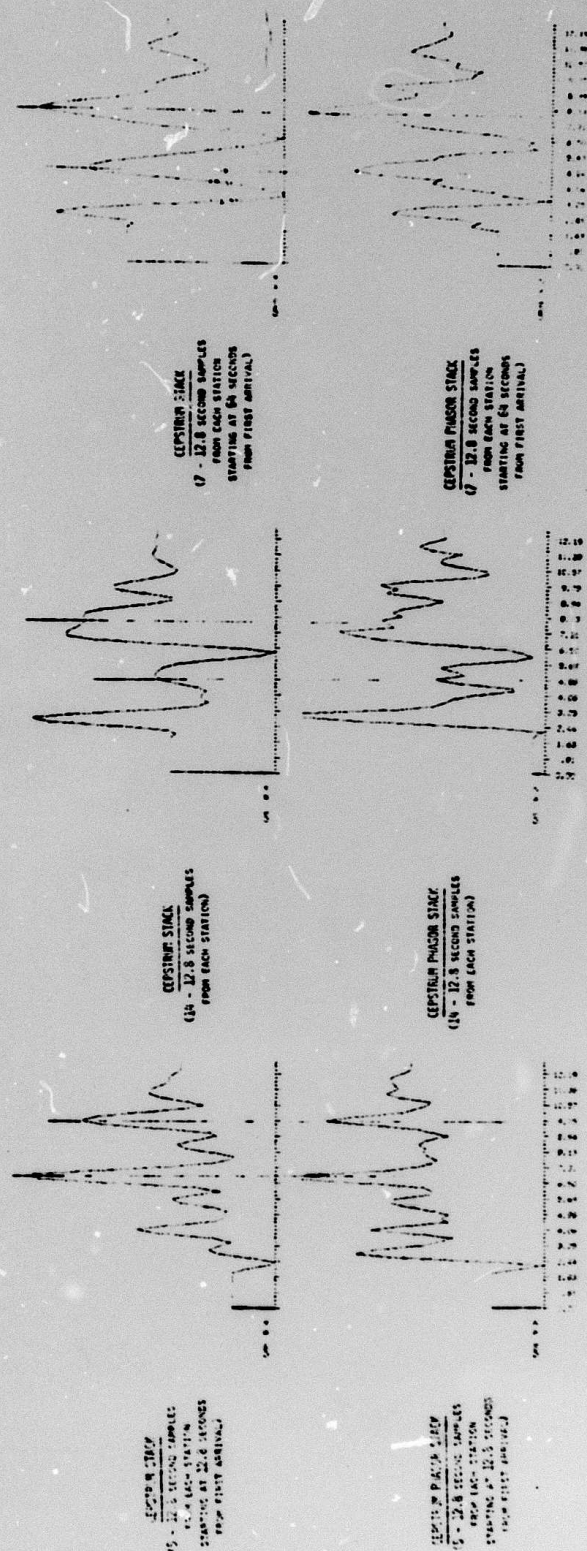


Figure 3a

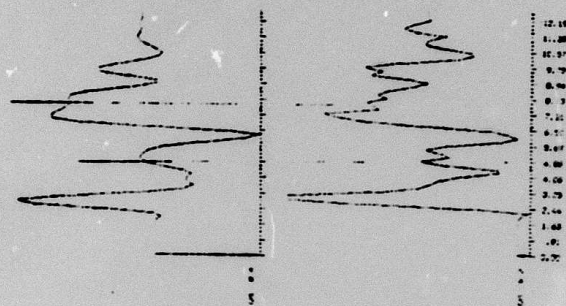


Figure 3b

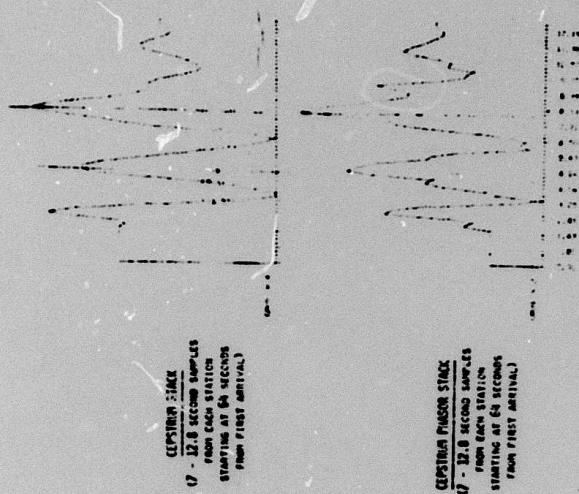


Figure 3c

ANALYSIS USING COMBINED DATA OF SIX STATIONS

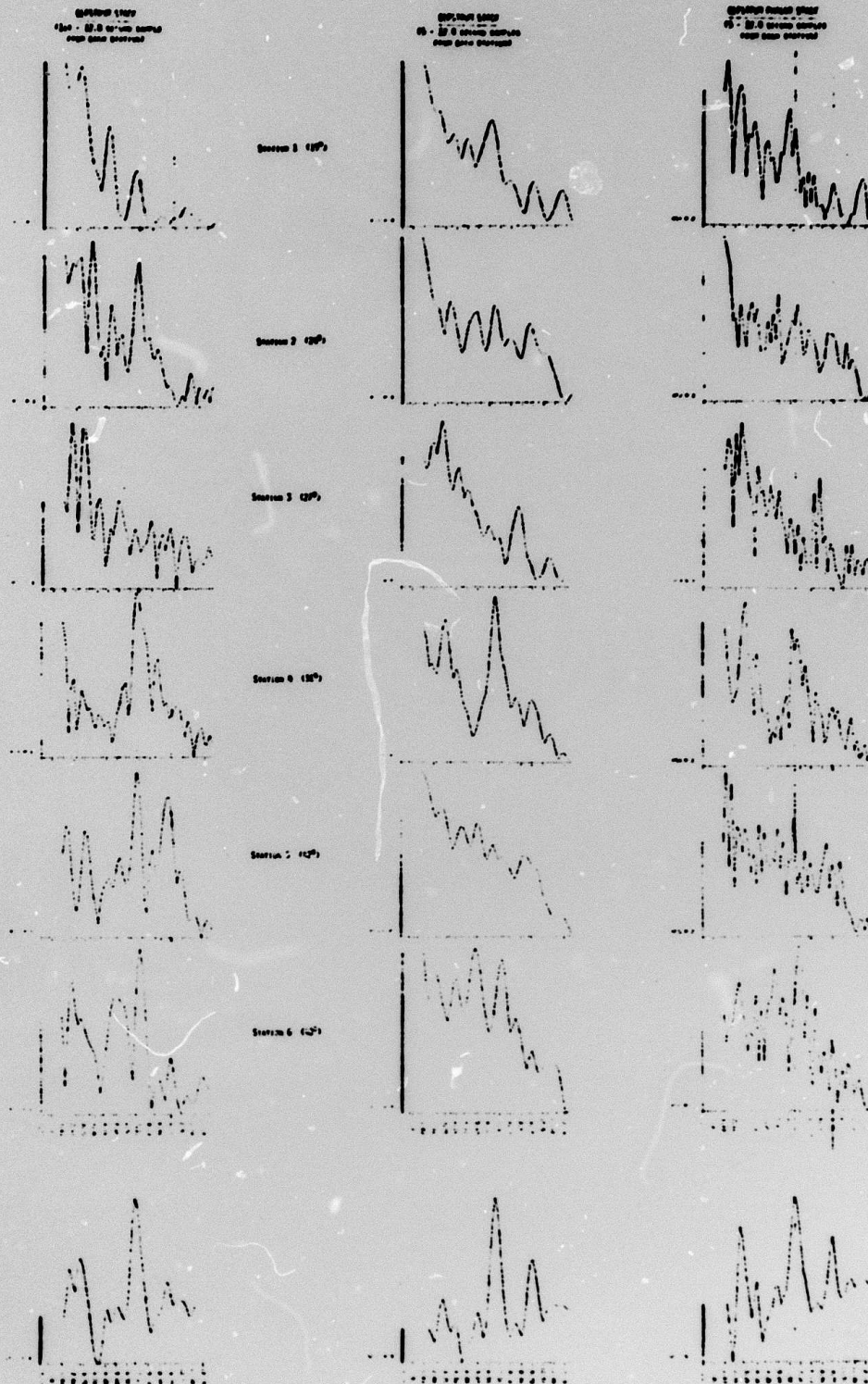


Figure 4

(pPP, sPP, pPcP, sPcP, etc.). Proper delay time scale adjustments can be made to allow these cepstrums to add constructively at the pP and sP delay times. Using such a procedure, one would be able to further improve detection by constructively using more of the coda than was used for the results of Figure 2. An example of the need for such a procedure can be seen in the analysis of the Illinois Event. In Figure 3c is the cepstrum resulting from the analysis using a portion of the coda starting ~1 minute from the first arrivals. As can be seen the cepstrum peaks are at 5 and 8 seconds possibly originating from the delay times of later phases such as pPP, sPP. The reduced detection resulting from averaging these cepstrums with cepstrums calculated from the first ~1 minute of the seismogram is seen in Figure 3b. Differential travel time information for these later seismic arrivals should enable better use of delay time information contained in the seismic coda.

Once good estimates of the cepstra are obtained, through the exploitation of information in the coda, the depth determination involves interpretation of typically complicated cepstrum patterns in conjunction with the travel time tables. This procedure can be automated and improved using a cepstrum matched filter technique. This involves assuming a particular cepstrum peak to be the pP time delay, referencing the travel time tables to find the expected sP time delay, and then correlating the computed cepstrum with the cepstrum pattern expected from these delays. In such a manner one can make a sequence of assumptions about possible depths and determine which assumption results in the best cepstrum match. Examples

of the usefulness of such a procedure are shown in Figures 5 and 6. In Figure 5 the cepstrum matched filter technique was applied to the cepstrum displayed in Figure 2c, and in Figure 6 this technique was applied to the cepstrum calculated using the data from MN-NV alone. In these figures, we see that the matched filter output indicates a dominant peak at ~7 seconds correctly corresponding to the pP-P time delay of ~7 seconds for the Illinois Event having a depth of ~25 km. In both cases the cepstral peak corresponding to the pP-P delay has emerged as the dominant peak in the matched filter output, whereas the cepstrums contained several equally dominant cepstral peaks. A procedure which would combine these cepstrum matched filter outputs for the different stations, while accounting for moveout, could be a very useful tool for the analyst in improving the extraction of source depth estimates.

Future Plans

We will apply these depth phase detection techniques to additional seismic events to better establish their role in the nuclear monitoring program while working on possible improvements to the depth determination procedure which are to be investigated during this contract.

CEPSTRUM

GMS CEP R

CEPSTRUM MATCHED
FILTER OUTPUT

GMS MFR R

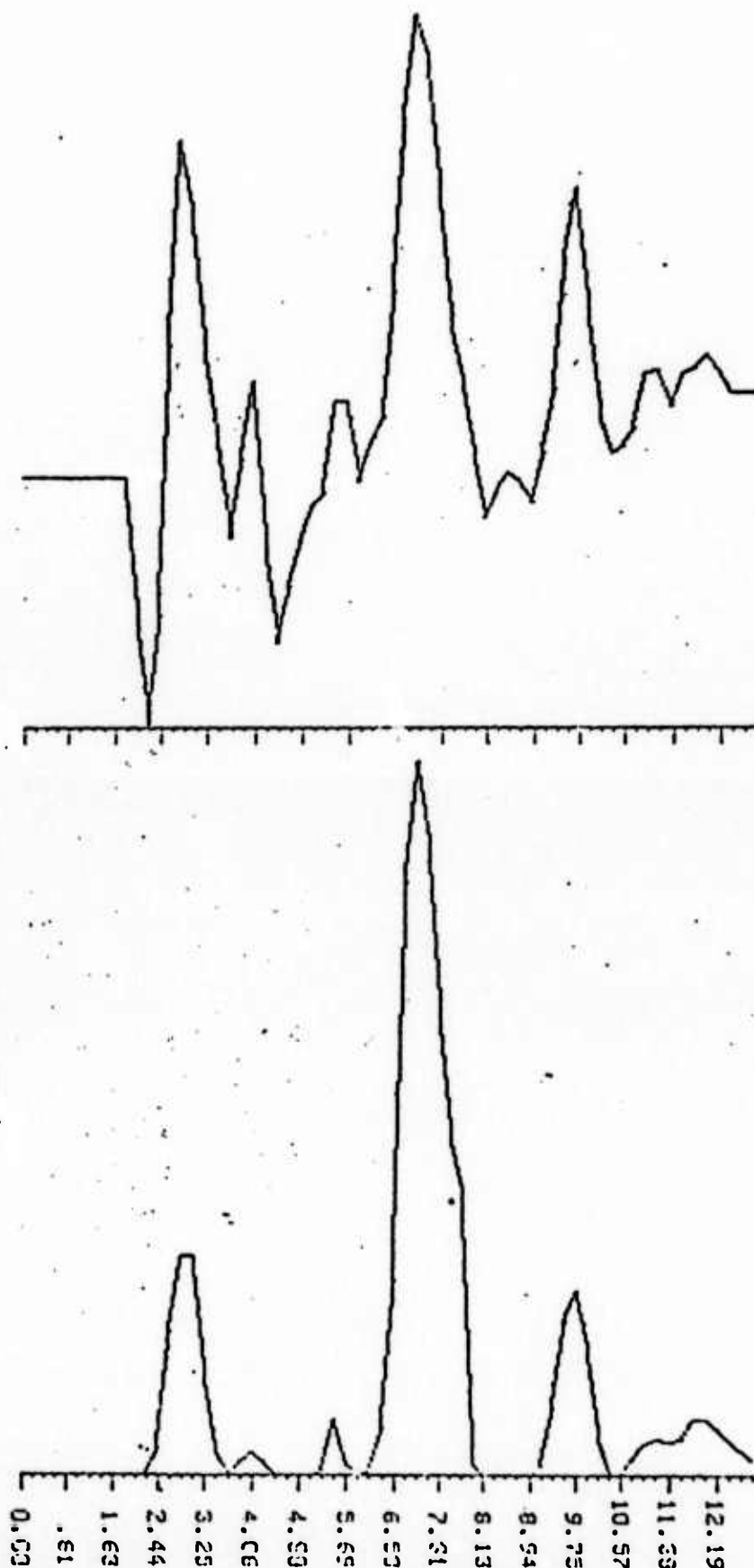
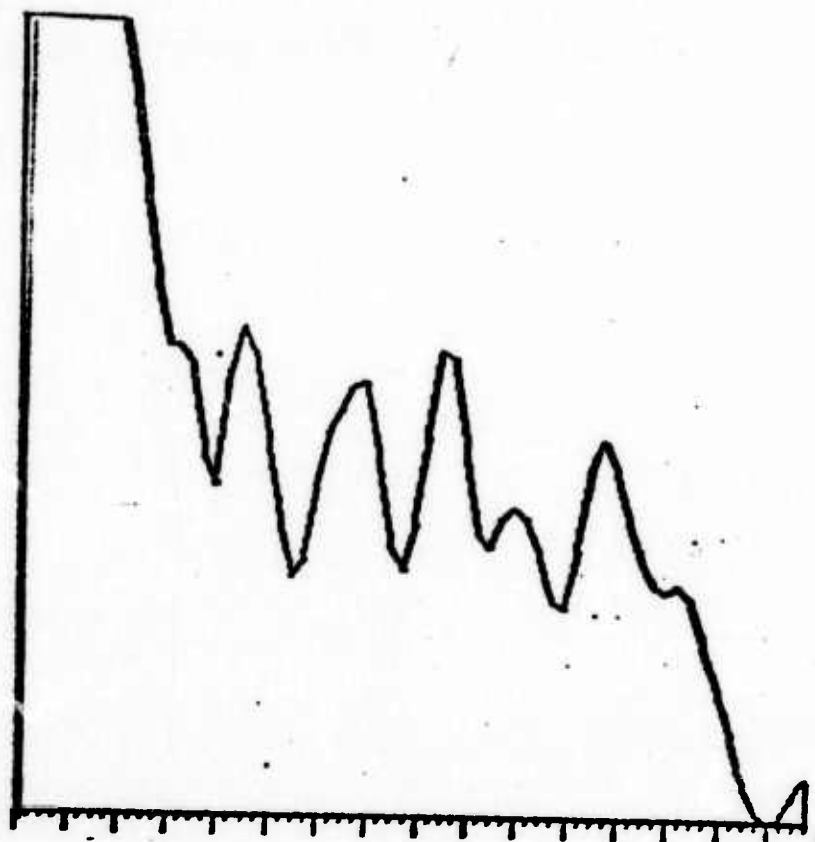


Figure 5

CEPSTRUM

MS2 R 4



CEPSTRUM MATCHED
FILTER OUTPUT

MS2 R 4

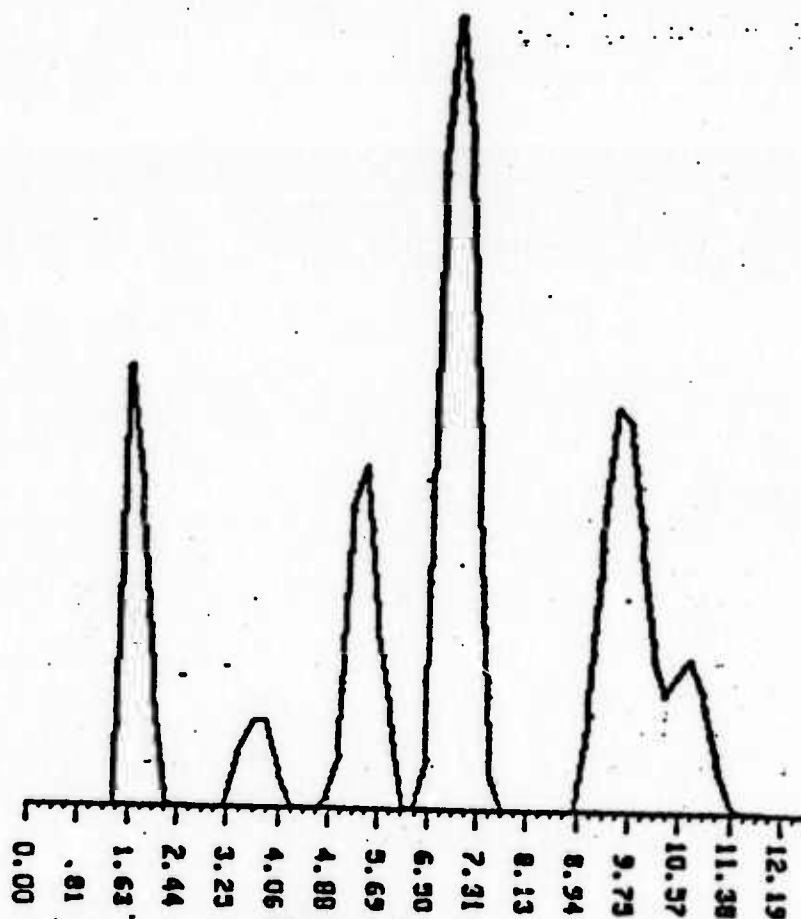


Figure 6